INTERACTION OF 30.8 GeV/c PROTONS WITH HEAVY EMULSION NUCLEI IN A STRONG MAGNETIC FIELD

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ABSTRACT. Interaction of secondary shower particles with photographic emulsion revealed that the former are mainly pions and protons; the latter constitute the majority of the charged particles formed.

Introduction

The present paper gives the results of a detailed experimental investigation of the properties of secondary shower particles, generated in interactions of high-energy protons with heavy nuclei of a photographic emulsion. /69

We used a stack of Ilford nuclear photo emulsions, type K-5, 600 microns thick, irradiated in a proton synchrotron at CERN by protons with an average momentum of 20.8 ± 0.3 GeV/c. Irradiation was performed in the presence of a pulsed magnetic field at a strength of 180 ± 4 kilooersteds, synchronized in time with the passage of a beam of primary protons. For more reliable measurements of the momenta of the charged particles, requiring exclusion of the values of local variations in the photographic emulsion (distortions), we performed an additional irradiation with protons having the momentum of 21.4 GeV/sec, perpendicular to the plane of the emulsion.

The use of the photographic emulsion method in conjunction with a powerful magnetic field makes it possible to achieve a reliable differentiation of the secondary particles on the basis of the sign of the charge and to perform highly accurate momentum measurements on a significant portion of the secondary charged particles. A study of the interaction of protons with heavy nuclei in the photographic emulsion in a strong magnetic field has already been performed at energies of 14 GeV [1] and 24 GeV [20], but in these papers the possibilities of the photographic method were not fully exploited (in particular, only an insignificant portion of the secondary shower particles were identified).

The analyzed experimental material consisted of 123 stars with a number of strongly ionized particles $n_h \geq 8$, located in the central portions of several photographic plates with minimal distortions and selected systematically from a large number of nuclear interactions which were found by inspection of the tracks. In the selected stars, we determined the spatial angles /70 of all charged particles from showers. Measurements of momentum (on the basis of track curvature) and ionization (using the method of cluster counting) with subsequent identification of the particles were performed on all shower particles (whose velocity data was greater than 0.7) at angles of inclination to the plane of the emulsion equal to or less than 20°. As a rule, several photo emulsion layers were used. In determining the magnitude of the momentum, corrections were introduced for the variations in the emulsion by making measurements of the beam tracks perpendicular to the plane of the emulsion, and a careful calibration of all layers used was performed in the ionization measurements. The average relative error in the measurements of momentum amounted to ~20%, while for exact ionization it was ~2%. The number of identified particles in our experiment was about 70% of the total number of shower particles. Each identified particle was assigned a statistical weight (geometrical factor) k in subsequent analysis:

$$k = \begin{cases} 1 & (\theta \leqslant 20^\circ;\ \theta \geqslant 160^\circ), \\ \dfrac{\pi}{2 \arcsin(\sin 20^\circ / \sin\theta)} & (20^\circ < \theta < 160^\circ). \end{cases} \quad (1)$$

The total number of shower particles (equal to 934.6), obtained after applying formula (1) to the identified particles, along with the desired number of shower charged particles $\Sigma n_s = 939$.

§1. Multiplicity, Composition and Angular Distribution of Shower Particles

In identifying the secondary shower particles using the "ionization-momentum" method, an ambiguity arises for those particles whose momenta are close to that used corresponding to the intersections of the ionization curves for particles of different mass. It is also extremely difficult to distinguish those particles which have similar masses and the same electrical charge (for example, positive hyperons and protons). The overwhelming majority of shower particles in our experiment (97%) had a momentum and ionization which

were in agreement with the ionization curves for pions and protons and only 3% could be reliably identified as kaons, deuterons, negative hyperons and electrons. Of course, the latter figure should be viewed only as the lower limit (due to the small numbers of these particles, they are as a rule not taken /71
into account in further analysis), and the number of pions and protons turns out to be slightly higher.

The composition of the charged shower particles (Table 1) was estimated on the basis of the following functions: 1) all shower particles with the exclusion of the reliably identified odd particles, deuterons and electrons, are pions and protons, 2) among the unreliably identified particles (the group p, π^+), which amount to approximately 9% of the total number of shower particles, the number of pions is equal to 0.3 ± 0.1 (see §2) regardless of the number of strongly ionized particles in the star.

In order to clarify the dependence of the characteristics of shower particles on the degree of development of the intranuclear cascade, we split up all of the showers which we investigated on the basis of the number of strongly ionized particles n_h into two groups with approximately equal populations: stars with $n_h < 16$ and those with $n_h \geq 16$. As we can see from Table 1, the average number of shower particles in the second group of showers is 1.5 times greater than in the first group, while the increase in the number of shower particles with an increase in the number of strongly ionized particles takes place primarily due to pions (the latter assertion, however, is not statistically reliable).

The angular distribution of shower particles on the scale of the value $x = \log|\text{cotan}\,\Theta|$ (Θ being the spatial angle of departure of a particle in the laboratory system of reference)[1] is shown at the bottom in Figures 1 and 2. /72
In constructing the histograms, we have proceeded on the basis of assumptions regarding the number of positive pions among the (p,π^+)-particles equal to 0.3 ± 0.1 regardless of the momentum of the (p,π^+)-particles (see §2), and

[1]In view of the fact that the amount of shower particles with $\Theta > \pi/2$ in our stars was small (approximately 4%), the distribution of this value is practically the same as the distribution of the conventionally employed $\lambda = \log \text{cotan}\,\Theta$.

the independence of the average transverse momentum of the shower particles with respect to the departure angle[2]. The angular distributions of protons /73
turn out to be narrower for all groups of showers, and the distributions of the positive and negative pions are practically the same, but as the number of strongly ionized particles in the stars increases there is a significant shift in the angle of distributions toward larger departure angles. This is supported by the data in Table 2 which list the empirical average values and dispersions (measures of anisotropy) of the distributions shown in Figures 1 and 2.

TABLE 1

Characteristics of the Particles	Type of Particle			All Particles
	p	n^+	n^-	
Average multiplicity:				
All stars	1.7 ± 0.1	2.9 ± 0.2	2.8 ± 0.2	7.6 ± 0.3
Stars with $n_h < 16$	1.5 ± 0.2	2.5 ± 0.3	2.0 ± 0.2	6.2 ± 0.4
Stars with $n_h \geq 16$	1.9 ± 0.2	3.4 ± 0.3	3.6 ± 0.3	9.1 ± 0.5
Fraction of total number of charged shower particles, %:				
All stars	22 ± 2	38 ± 3	37 ± 3	100
Stars with $n_h < 16$	24 ± 3	40 ± 4	33 ± 4	100
Stars with $n_h \geq 16$	21 ± 2	38 ± 3	39 ± 3	100

TABLE 2

Group of Stars	Average value $\bar{x}$-100				Dispersion $\sigma^2(x)$-100			
	n^+	n^-	p	All	n^+	n^-	p	All
All stars	33 ± 2	31 ± 3	59 ± 3	38 ± 1	19 ± 2	28 ± 3	20 ± 2	26 ± 2
Stars with $n_h < 16$	40 ± 4	49 ± 4	73 ± 4	51 ± 3	20 ± 3	19 ± 3	18 ± 3	24 ± 2
Stars with $n_h \geq 16$	26 ± 3	19 ± 4	48 ± 4	28 ± 2	16 ± 2	29 ± 3	19 ± 2	28 ± 2

[2]We showed in §3 that such an assumption is incorrect for protons, but the extent of this discrepancy is not so great that it causes a significant distortion of the angle of distributions.

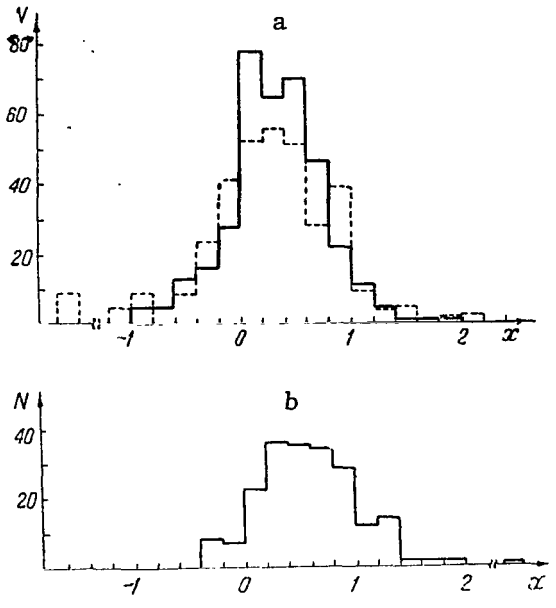

Figure 1. Angular Distribution of Shower Particles: a, Positive (solid line) and negative (dotted line) pions; b, Protons.

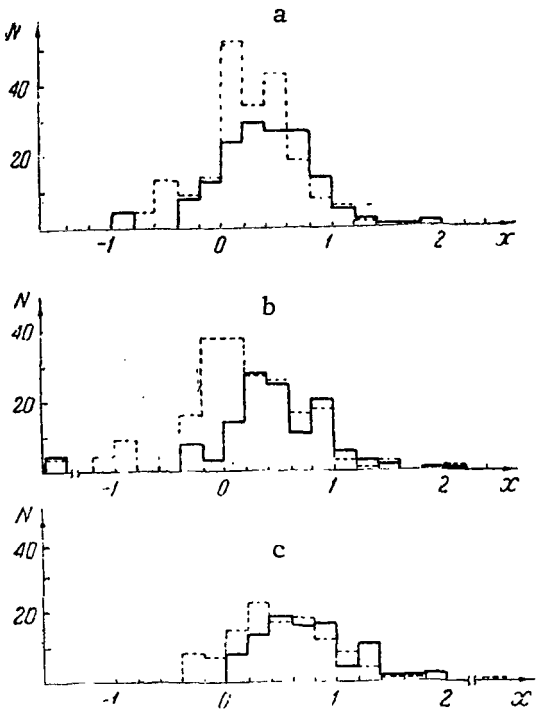

Figure 2. Angular Distribution of Shower Particles in Stars with Different Numbers of Strongly Ionized Particles: a, Positive pions; b, Negative pions; c, Protons: Solid line equals stars with $n_h < 16$, dotted line equals stars with $n_h \geq 16$. /74

§2 Momentum Distributions; Composition of Ambiguously Identified Particles

In momentum distributions of different types of identified particles (Figure 3) we observed gaps in the range $1.5 < p < 3$ GeV/c for protons and positive pions, caused by the impossibility of identifying particles with /75 the same sign of charge using the method of "ionization-momentum" at the points of intersection of the ionization curves. However, the majority (80%) of ambiguously identified particles with positive charge (group (p,n^+)) are concentrated in a comparatively narrow range of momenta.

To clarify the problem of the number of pions and protons among the particles in group (p,π^+), we are making two independent assumptions. The first is that the momentum distributions of the protons and pions of both signs are described by some continuous function, for example,

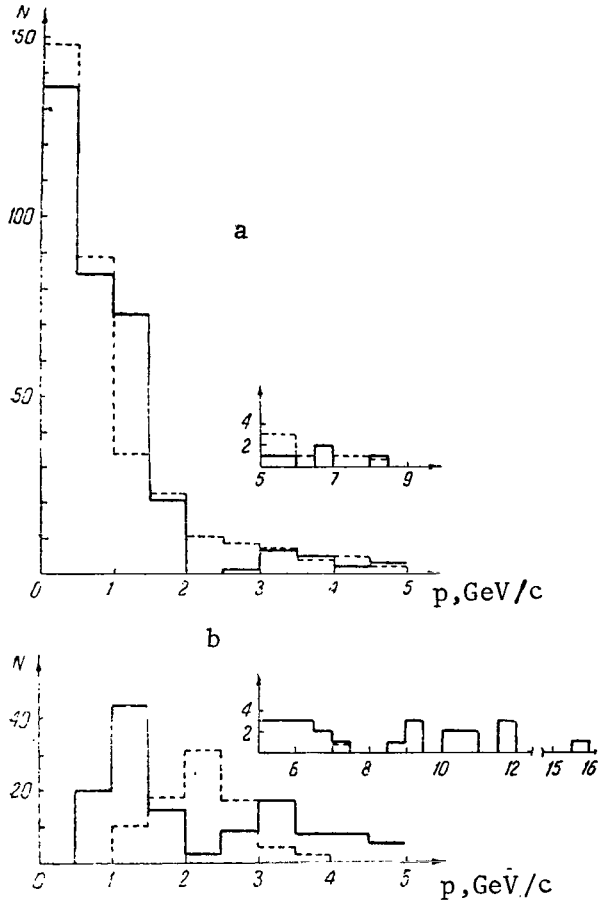

Figure 3. Momentum Distribution of Identified Particles: a, Positive (solid line) and negative (dotted line) pions; b, Protons (solid line) and (p, n^+)-particles (dashed line).

$$a(p-b)^{-m},$$

where b is a value equal to 0.2 GeV/c for pions and 1.2 GeV/c for protons[3]; a and m are constants determined empirically on the basis of the portions of the distributions in the ranges $p < 1.5$ GeV/c and $p > 3$ GeV/c for protons and π^+ mesons. Secondly: the number of π^- mesons in the range $1.5 < p < 3$ GeV/c is equal to the number of π^+ mesons in the same interval, while the number of the latter in the group of (p,π^+)-particles is independent of the momentum. Each of the above assumptions leads to an estimate of the number of positive pions among the group of (p,π^+)-particles equal to $(30 \pm 10)\%$. Similar figures can be obtained by an analysis of the angular, energetic and other distributions of particles but due to their dependence upon the momentum, these estimates are largely indirect. /76

In our further analysis, if we do not make a special notation, we will always be using the assumption regarding the number of positive pions among the (p,π^+)-particles, equal to 0.3 ± 0.1 regardless of the momentum of the (p,π^+)-particles. The momentum distributions of positive and negative pions (Figure /78

[3]At values of the proton and pion momenta below the indicated values, the effectiveness of the recording under the conditions of our experiment was considerably less than unity due to measurement errors.

4.5) turned out to be practically the same for both small and large n_h, differing considerably from the momentum distribution of the protons. We also observed a considerable "softening" of the momentum spectra of all types of shower particles with an increase in the number of strongly ionized particles in showers (see Figure 5).

TABLE 3

Characteristic	Energy of Secondary Particle			
	Greater than $0.2\ E_0$	Greater than $0.3\ E_0$	Greater than $0.4\ E_0$	Greater than $0.5\ E_0$
Number of protons n_p	37.4 ± 6.4	18.7 ± 4.3	12.0 ± 3.5	8.0 ± 2.8
Number of charged ions n_π:				
Total	28.3 ± 5.3	7.3 ± 2.7	2.0 ± 1.4	--
Positive	10.3 ± 3.2	3.3 ± 1.9	1.0 ± 1.0	--
Negative	18.0 ± 4.2	4.0 ± 2.0	1.0 ± 1.0	--
Number of protons, %	18.1 ± 3.0	9.1 ± 2.1	5.8 ± 1.7	3.9 ± 1.4
Number of charged pions, %	4.0 ± 0.8	1.0 ± 0.4	0.3 ± 0.2	--
n_p/n_π	1.3 ± 0.3	2.6 ± 1.1	6.0 ± 4.6	--

In conjunction with theoretical models of nuclear interactions at high energies, we were quite interested in the fact that a particle which conveys maximum energy in a nucleon-nucleon (NN) interaction is a nucleon. If we consider the nucleon-nuclear interactions as a combination of several successive NN-interactions, the nucleons in them will be energetically separated. An analysis of the high-energy "tail" in momentum distributions (see Figure 4 and 5) shows that the principal mass of secondary charged particley of high energy is composed of protons (Table 3).

§3. Distribution of Transverse Momenta

The transverse momentum ($p_\perp$) of secondary particles is one of the most important characteristics of the process of multiple production of particles at high energies. A number of empirical properties of the $p_\perp$-distributions (the shape of the distribution, the average value of $p_\perp$ and its dependence upon the

energy of the primary particle, the natures of the secondary particles, departure angles, etc.) are widely employed in the analysis of the mechanism of interaction and the construction of theoretical schemes of the process [3].

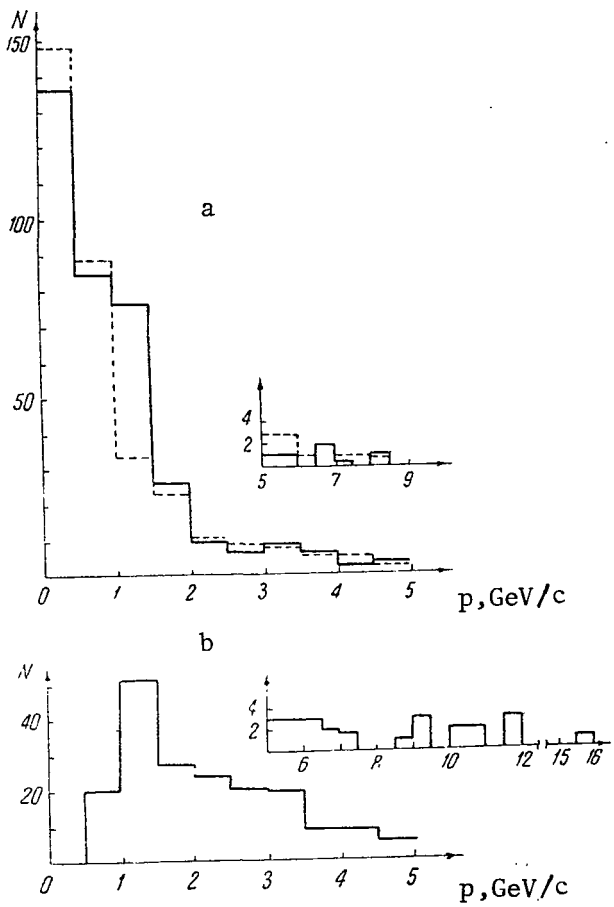

Figure 4. Momentum Distribution of Shower Particles: a, Positive (solid line) and negative (dotted line) pions; b, Protons.

In §2 we found that among the ambiguously identified (p,π^+)-particles a majority are protons. Therefore, in analyzing the distributions of the transverse momenta we can view as "protons" a combined group of p- and (p,π^+)-particles which in our estimates were "contaminated" with π^+ mesons by no less than 10-15%. This assumption is also justified *a posteriori*: in all the distributions $p_\perp$ given in the present section, the partial distributions of the p- and (p,π^+)-particles within the limits of error are correct and significantly different at the same time from similar distributions of pions.

Firgure 6 shows the corresponding differential and intergral distributions with respect to $p_\perp$ for various types of secondary shower particles from the analyzed class of interactions and the curves corresponding to the simplest of the widely used forms of $p_\perp$ distribution /79

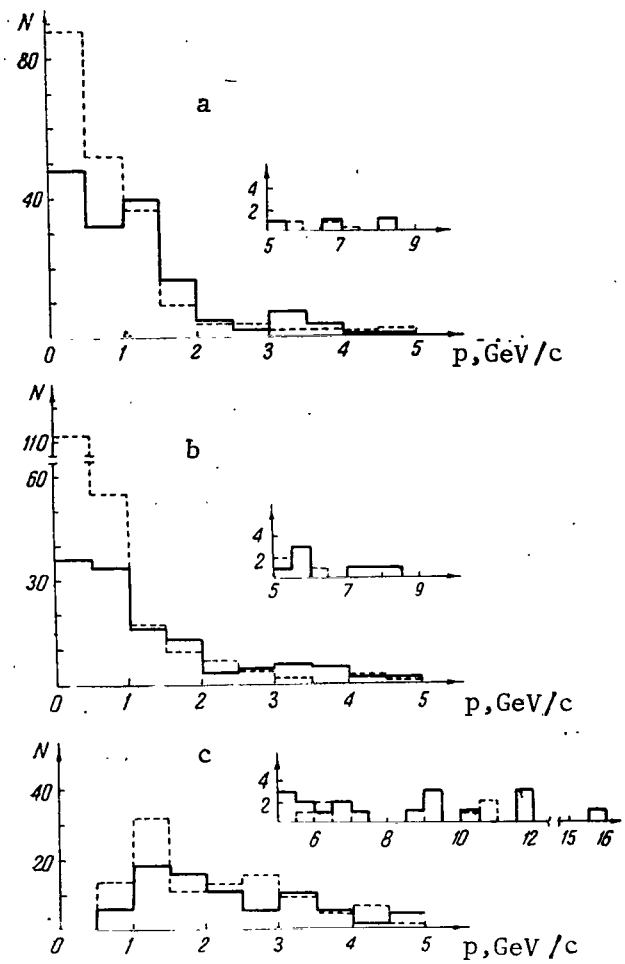

Figure 5. Momentum Distribution of Shower Particles in Showers with Different Numbers of Strongly Ionized Particles: a, Positive pions; b, Negative pions; c, Protons; Solid Line indicates showers with $n_h < 16$, Dotted line indicates showers with $n_h \geqslant 16$.

$$f(p_\perp)\,dp_\perp = \alpha^2 p_\perp \exp(-\alpha p_\perp)\,dp_\perp \quad (2)$$

and

$$f(p_\perp)\,dp_\perp = 2\beta p_\perp \exp\left(-\beta p_\perp^2\right)\,dp_\perp, \quad (3)$$

whose parameters correspond /80 to the observed average values of transverse momenta $\overline{p_\perp}$ equals 0.32 for pions and 0.64 for protons (curve number one in Figure 6 is normalized for the average of the mutually similar numbers of positive and negative pions).

Average Values of Transverse Momenta of Shower Particles $\overline{p_\perp}$

p	0.64 ± 0.03
π^+	0.33 ± 0.02
π^-	0.31 ± 0.02
All	0.40 ± 0.01

On the basis of these data, we can conclude that:

$p_\perp$ distributions of positive and negative pions within the limits of error are the same; the average value of $\overline{p_\perp}$ for these particles is nearly the same as the corresponding value for NN-interactions [4]; the average transverse momentum of protons is twice as great as $p_\perp$ for pions and is significantly greater than the value observed in NN interactions.

The form of the $p_\perp$ distribution has the satisfactory approximation to the exponential function (curve one in Figure 6) for pions and to the Boltzmann function (curve two) for protons as well as for NN interactions [3].

The transverse momentum of the pions is nearly independent of the departure angle (Figure 7a) if we do not take into account its reduction in the region of small angles, which can be explained by the influence of the law of conservation of momentum. The transverse momentum of the protons with increasing departure angle shows considerable increase. Figure 7b illustrates a significant reduction in the transverse momenta at small absolute values of the momentum of the shower particles. The transverse momentum of protons with a momentum $p \gtrsim 2$ GeV/sec and pions with a momentum $p \gtrsim 1$ GeV/sec is practically constant and equal to 0.7 and 0.5 GeV/sec, respectively. The fact that the average transverse momentum of protons in "nucleon-solid nucleus" collisions is considerably greater (twice as large) than the average transverse momentum of the pions, is largely due to the fact that a large portion of the shower particles are extremely low-energy pions formed in the process of intranuclear cascading.

The distributions of transverse momenta of all types of secondary shower /81
particles in stars with different numbers of highly-effective particles within the limits of error of the experiments were the same. This result is not unexpected, since as n_h increases, two mutually compensating processes occur: expansion of the angular distribution and "softening" of the momentum distribution (see § 1 and 2). The effect of the increase in the transverse momenta of protons with departure angles however is associated primarily with stars having large numbers /82
of ionized particles, which clearly indicates a cascade mechanism for their development.

§4. Inelasticity and the Energy Balance

Calculation of the energy balance of secondary particles (Table 4) was performed with the following assumptions (in addition to those made in §2):

Multiplicity and kinematic characteristics of the π^0 mesons coincide with the analogous characteristics for charged pions;

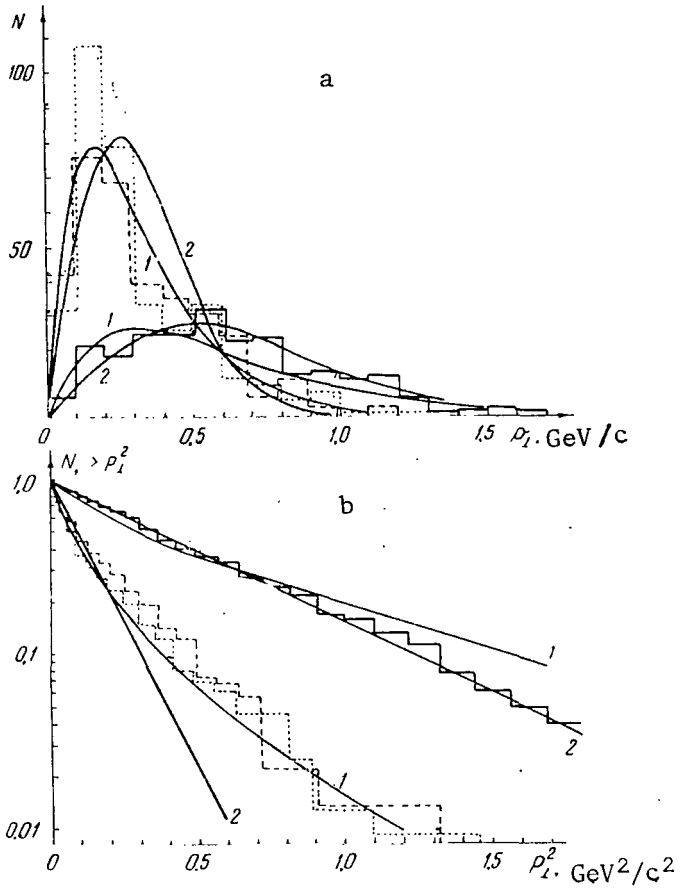

Figure 6. Differential (a) and Integral (b) Distribution of Transverse Momenta of Shower Particles: The solid line represents "protons", the dashed line represents positive pions, and the dotted line represents negative pions; 1, Curves (2); 2, Curves (3).

The average energy for one strongly ionized particle in collisions between fast particles (with energies in tens of GeV, for example) and heavy nuclei is independent of the energy of the shower and the number of highly ionized particles [5, 6] and equal to the weighted average value of this quantity from [1, 2, 5].

An examination of the data in Tables 1 and 4 will show the energy distribution between the different types of secondary shower particles in collisions of fast protons with heavy nuclei is only slightly dependent on the degree of /83

development of the intranuclear cascade (number of strongly ionized particles), and an increase in the number of shower particles with an increase in the number of strongly ionized ones is accompanied by a "softening" of the energy spectrum to an extent such that the total energy associated with each type of shower particle remains approximately the same. A similar picture is observed in collisions of 17 GeV /c pions with heavy photo emulsion nuclei [5].

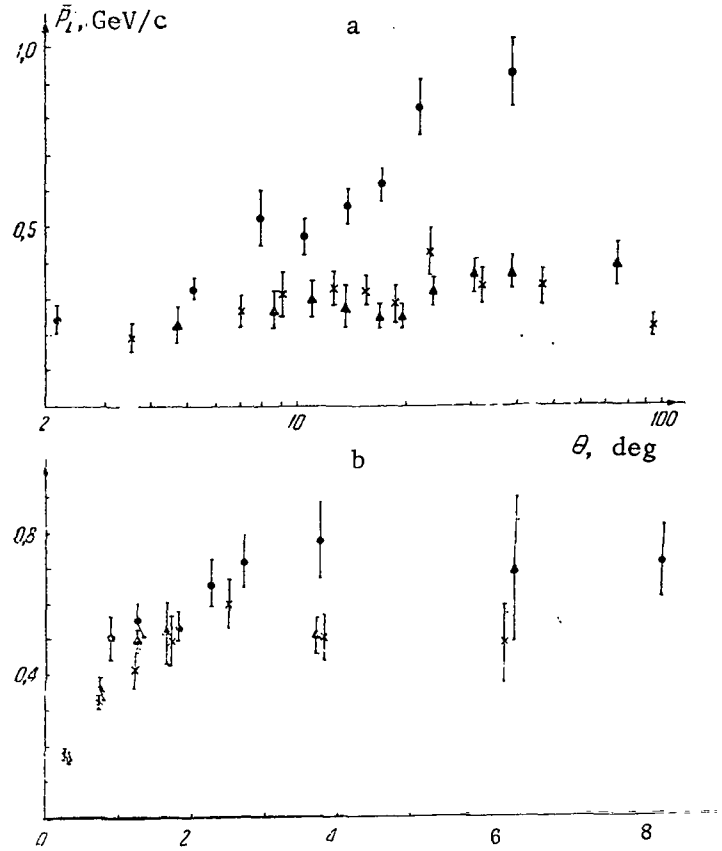

Figure 7. Relationship of the Average Transverse Momentum of Shower Particles on the Departure Angle (a) and Momentum (b): ▲, positive ions; ×, negative pions; ●, "protons".

TABLE 4

Type of particle	All stars		Stars with $n_h \leqslant 16$		Stars with $n_h \geqslant 16$	
	$\overline{T}$[1], GeV	k[2], %	$\overline{T}$[1], GeV	k[2], %	$\overline{T}$[1], GeV	k[2], %
Positive pions	2.7±0.4	13.6±1.6	2.7±0.6	13.6±2.8	2.7±0.5	13.5±2.5
Negative pions	2.7±0.3	13.5±1.4	2.9±0.5	14.6±2.4	2.5±0.4	12.3±2.0
All pions[4]	8.1±0.6	40.6±2.9	8.4±0.9	42.3±4.3	7.8±0.8	38.9±3.9
Protons	3.6±0.5	17.9±2.4	3.8±0.7	19.3±3.2	3.3±0.7	16.5±3.4
Other shower particles[3]	0.3	1.4	0.3	1.5	0.3	1.3
Highly ionized particles[4]	2.2±0.4	11 ± 2	1.4±0.3	7 ± 2	3.0±0.5	15 ± 3
Rest Energy of mesons[4]	1.3±0.4	6.4±0.5	1.0±0.1	5.1±0.4	1.5±0.2	7.6±0.8
Balance (primarily neutrons)	4.4±1.0	22 ± 5	5.0±1.3	25 ± 7	4.0±1.2	20 ± 6

[1]Average kinetic energy conveyed to a given type of particle in one collision.
[2]Amount of kinetic collision energy conveyed to a given type of particle.
[3]The numbers in this line of the table must be viewed as a lower limit.
[4]Including neutral ones.

Results

1. The overwhelming majority of charged shower particles are pions and protons.

2. All kinematic and dynamic characteristics of positive and negative pions in all groups of showers are the same within the limits of error of the experiment.

3. Protons in the laboratory system of reference escape at smaller angles than the pions; they also constitute a majority among the most energetic charged particles.

4. The average transverse momentum of protons is twice as great as the corresponding value of pions, which is explained primarily by the large number of

very low-energy pions among the shower particles.

5. The transverse momentum of pions is nearly independent of the departure angle; however, for protons there is a significant increase in the average transverse momentum with departure angle; this effect is obviously explained by the cascade mechanism of secondary particles which in the case of pions does not lead to a similar phenomenon due to the very large number of low-energy pions that escape at large angles.

6. The increase in the degree of development of the intranuclear cascade (number of strongly ionized particles) is accompanied by a significant increase in the number of secondary shower particles as well as an expansion of the angular energy distribution and "softening." The distribution of the transverse momenta and the amount of energy conferred by different types of shower particles is practically independent of the number of strongly ionized particles in the shower.

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